Synopsis of the thesis entitled

STATUS OF BOMBAY DUCK FISHERY, DISTRIBUTION AND BIOLOGY ALONG THE WEST COAST OF INDIA

Submitted by

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The present investigation, entitled "**Status of Bombay duck Fishery, Distribution and Biology along the West Coast of India**," is discussed under different sections.

Chapter 1: General Introduction

The Bombay duck (*Harpadon nehereus*) belongs to the family Synodontidae and is found in the coastal regions of South Asia, the Middle East, northeast Australia and Southeast Asia up to the east coast of China (FishBase, 2019). This species plays an important role in small-scale fisheries and supports the livelihoods of coastal communities in various states bordering the Bay of Bengal, including India (Shingadia, 2013), Bangladesh (Ullah et al., 2014) and Pakistan (Kalhoro et al., 2013).

In India, about 90% of Bombay duck caught on the northwest coast comes from the coastal states of Gujarat and Maharashtra. In addition, a significant proportion comes from West Bengal and Orissa on the northeast coast (Kurian, 2003). The total landing of Bombay duck was 1,10,417 tons in 2015, representing roughly 3.24% of the total marine landings (3.40 million tons). The pelagic landings accounted for about 1.70 million tons (CMFRI, 2016). The primary method of harvesting Bombay duck is by using stationary bag nets, locally known as "dolnet". A seasonal shift has been observed in the occurrence of the Bombay duck in both coastal and deeper waters (Ghosh, 2014).

Cumulative global marine fish catch has shown a declining trend since 2015. The 2016 figures recorded a total global marine fish catch of 79.3 million tons, compared to 81.2 million tons the previous year (FAO, 2018). Meanwhile, marine fish catches along the Indian coast witnessed a significant boost, reaching an estimated 3.83 million tons in 2017, registering a notable increase of 5.6% compared to 3.62 million tons in 2016. Within India, Gujarat was the main coastal state contributing to this increase, reporting the highest catches among all maritime states and union territories. From 2013 to 2016, Gujarat landed an average of 0.73 million tons annually, accounting for more than 20% of the country's total marine fish landings.

Marine fish landings off the coast of India were estimated at 3.53 million tons in 2023, up slightly from 3.49 million tons in 2022, an increase of about 1.2%. Compared to 2021, this indicated a notable increase of 15.75%. Gujarat recorded the highest landings of 0.823 million tons, followed by Kerala with a landing 0.63 million tons and Karnataka with 0.60 million tons

(Gopalakrishnan 2024). In 2016, Bombay duck was the second-largest fishery among pelagic finfish, contributing 0.09 million tons to India's total marine fish landings, while in 2023, the mainland recorded 3.53 million tons of landings, with Bombay duck accounting for 0.73 lakh ones. (CMFRI, 2017; Gopalakrishnan, 2024).

The distribution of the Bombay duck is influenced primarily by two key factors: food availability and water temperature conditions (Bapat, 1970; Ghosh, 2014; Raj, 1954). Significant quantities of Bombay duck are landed along the northwest coast, with the fishery relying primarily on smaller fish (Kurian, 2003). Compared to other fish, Bombay duck has a higher water content of 66% and is highly perishable. Only a small portion of the catch is consumed fresh, while the remaining fish is sun-dried (Figure.1) on specially constructed bamboo platforms. In times of glut, the spoiled catches are used for fertilizer production.

1.1 Scope

The Bombay duck fishery in India has a discontinuous distribution pattern restricted to the northern latitude between 18°N and 22°N (northwest coast - Gujarat, Maharashtra and northeast coast - West Bengal, Odisha) (Bapat, 1970). Almost 90% of Bombay duck landings occur on the northwest coast. This discontinuous distribution is attributed to the typical tidal amplitude at the northern latitude of the Indian coast. The abundance of shrimp and anchovies associated with the tidal fluctuations in this region makes it favorable for Bombay duck in terms of food availability and easy access. Bombay duck plays a crucial role in the overall pelagic landings along the west coast of India. Any change in their production is reflected in total fish landings.

Figure 1.1: Sun-Drying of Bombay duck

There is a gap in our knowledge about the fisheries, biology and population status of the Bombay duck from Indian waters. In addition, fluctuations in catches and decline in total landings

in recent years are of concern to fisheries scientists and planners. The present study provides a comprehensive overview of the status of the fishery, biological characteristics and stock assessment with relevant recommendations for the management of this important fish along the west coast of India. A significant part of this research will be dedicated to elucidating the biological aspects of the Bombay duck. This includes a study of its life cycle, reproductive patterns, growth rates and feeding habits. Understanding the biology of the species is crucial to understanding its role in the ecosystem and developing effective management and conservation strategies. The results of the study will help develop sustainable approaches for the prudent management of the Bombay duck stock along the west coast of India.

1.2 Objectives

The objectives of the thesis work are:

1.2.1 To analyse the fishery and distribution trends of Bombay duck along the west coast of India.

1.2.2 To examine the food and feeding habits of Bombay duck landed along the west coast of India.

1.2.3 To investigate the reproductive biology of Bombay duck exploited along the west coast of India.

1.2.4 To assess seasonal variations in the population and stock structure of exploited Bombay duck fishery.

The four objectives are addressed individually in four separate chapters. In particular, these chapters do not contain a schematic description of the species, their special characteristics or their geographical distribution. Instead, the significance of the study is explored and explained in detail, along with its objectives and a detailed overview of the thesis, in the introductory section in Chapter 1.

Chapter 2: Distribution trends and seasonal variations in the exploited Bombay duck fishery

2.1 Introduction

The Bombay duck has contributed significantly to India's commercial fisheries, particularly along the Saurashtra Coast (Ghosh, 2014). An analysis of marine landings over time shows a 52.4% increase (3.21 million tons) in landings from 2001 to 2008, followed by a 2.2% decrease from 2008 to 2010. There was then a notable increase from 2010 to 2017 of 20.2%, which peaked during 2017 to 2022. However, there was a significant decrease of 23.4%, (3.49 million tons) in 2022.

A similar pattern was observed in landings of pelagic fishes, from a 19.3% increase to 1.69 million tons by 2008, a 1.8% decrease by 2010, and a subsequent 22.8% increase to 2.07 million tons by 2017. In 2022, pelagic landings reached 1.99 tons. The total landings of Bombay duck remained relatively stable, with an increase of 34.3% (0.11million tons) from 2001 to 2010 to a further increase of 15.0% (0.12million tons) by 2013 followed by a decrease of 6.3% (0.055million tons) in 2022. The fishing activity was mostly concentrated in a relatively narrow zone of 45 kilometers from the shore at depths between 20 and 70 meters.

In Gujarat, the main Bombay duck landing sites are Nawabunder, Saiyad Rajpara and Jafrabad (Ghosh, Pillai and Dhokia, 2009). The fishermen in these centres mainly use the “Dolnet”, a fixed fishing gear. These stationary dolnets operate on the basis of tidal forces, and their activities during the fishing are traditionally guided by voluntary regulations from fishermen associations. During the beginning of the fishing season, catch rates are generally high and a single haul is sufficient to sustain the dolnet operation. However, as fishing season progresses, the catch of Bombay duck declined and the fishermen make 2-3 hauls. The dolnets have a length range of 35 to 60 meters and the codend mesh size is 20 millimeters (Ghosh et al., 2009). It is interesting to note that about 92% of the Bombay duck catch came from mechanized dolnets (CMFRI, 2017).

Numerous surveys have been carried out on the Bombay duck fishery in Indian waters, particularly along the Saurashtra Coast (Gokhale, 1957; Hora. 1934; Setna, 1932). While Bapat (1970) extensively documented the biology and fisheries of the Bombay duck, Bapat and Alawani, (1973) specifically studied the fishery in Maharashtra, focusing on Versova. A comprehensive study on Bombay duck along the coasts of Gujarat and Maharashtra during 1950 to 1972 was carried out by Nair and Balakrishnan (1975). Deshmukh and Kurian (1980) researched on the

fishery and biology of the Bombay duck along the Indian Coast. Khan (1983, 1986b, 1987) reported on the occurrence of Bombay duck off the coast of Gujarat, with particular attention to the Gulf of Kutch, Nawabunder and Jafrabad. Kurian (1988, 1989) focused on fisheries off the Coast of Maharashtra. The Bombay duck fishery in Versova, Bombay has been described in detail by Raje and Deshmukh (1989) and Ghosh (2014). Khan et al. (1992) reported on the fishery off the Saurashtra Coast. The status of stocks and the response of the fisheries to exploitation were examined by Kurian (2000). Balli et al. (2011) conducted research on Bombay duck fishery in Mumbai waters. Additionally, research on the Bombay duck fisheries in international waters has been conducted by several researchers (Luo et al., 2012; Tarakan et al., 2015).

2.2 Material and Methods

The datasets used to study the Bombay duck fishery in India included information on total annual marine landings, the pelagic fish landings and the Bombay duck landings. These data were sourced from the annual reports of the Central Marine Fisheries Research Institute from 1990-91 to 2016-17 (Anon n.d.). The monthly and annual catch and effort estimates for the study periods were obtained from the Fishery Resource Assessment Division (FRAD) of the CMFRI (CMFRI). Fishing activities along the coast occurs continuously throughout the year, with the exception of June to August, when a general fishing ban for mechanized crafts is imposed on the west coast.

2.3 Results and Discussion

The Bombay duck landings over the years (1990 - 2016) has steadily declined despite annual and seasonal fluctuations. The highest landing was recorded in 2013 (0.12 million tons) and the lowest in 2022 (0.055 million tons). The decline in Bombay duck landings is significant and the probable reasons for the decline has been attributed to both biotic, abiotic factors.

The percentage changes in landings over the 21-year period (2001 – 2023) was analysed and Figure 2.3.1 highlights landing trends of total marine, pelagic and Bombay duck resources. The total marine fish landings increased by 51.96%, indicating growth in marine fisheries. The landings of pelagic fishes also increased by 67.47%, indicating an increase in the catch of pelagic species. However, the abundance of Bombay duck decreased by 35.46%, probably indicating a decline in the prey abundance of Bombay duck.

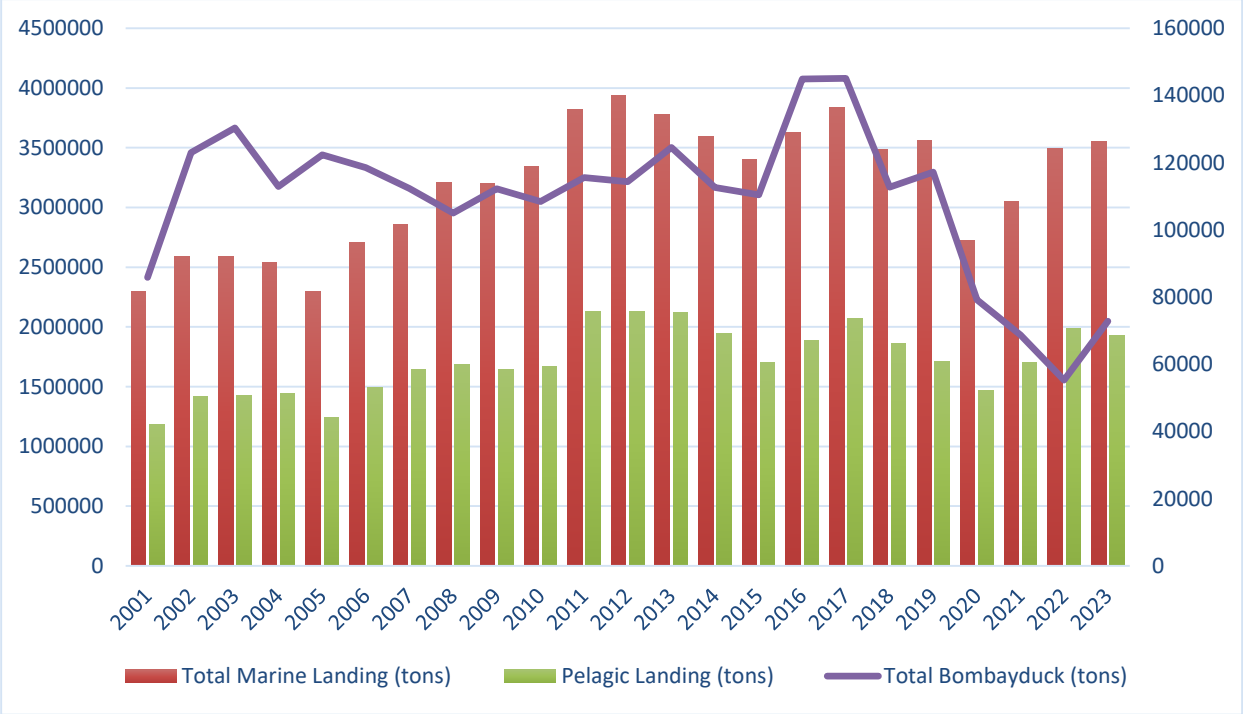

Figure 2.3.1: Fishery trends of Bombay duck landings in India (2001 – 2023).

The Bombay duck fishery in Gujarat is mainly carried out from Jafrabad, Nawabunder and Saiyad Rajpara the major fishing centers. Fishing in these places is primarily made using dolnets and focuses exclusively on the harvest of a single species, *H. nehereus* (Hamilton, 1822). September recorded the highest CPUE percentage for Bombay duck and contributed 55.26% to the total catch. In contrast, August recorded the lowest CPUE percentage and accounted for only 12.45% of the total catch.

The Bombay duck fishery was good during both the fishing seasons of 2014–2015 and 2015–2016. The total catch of the Bombay duck (*H. nehereus*) reached an impressive 0.14 million tons. The catch was made by 3,84,718 fishing units operating along the Indian Coast (Table 2.3.1).

This total marine fish catches with a significant presence of *H. nehereus* in the region, highlights the crucial role of this commercially important species in supporting the livelihoods and food security of people working in the fisheries sector of the region.

Detailed fishery, biology and population structure was made on samples collected during the study period including the two fishing seasons in 2014-15 and 2015-2016.

Table 2.3.1: Estimated month-wise effort, catch and catch rate of Bombay duck in dolnets operated along Gujarat during 2014 –2016 (Pooled).

Pooled Seasons (2014-2016)						
Month	**Effort (Units)**	**Effort (Fishing Hours)**	**Total Catch (t)**	**Bombay duck Catch (t)**	**CPUE**	**%**
Sep	28950	456060	36300	20060	692.91	55.26
Oct	39195	802343	59429	23906	609.93	40.23
Nov	42196	834184	58291	24926	590.71	42.76
Dec	32922	718058	49739	18190	552.51	36.57
Jan	27449	599320	35757	12935	471.25	36.18
Feb	28164	440064	16634	4252	150.97	25.56
March	26389	528977	52205	10273	389.29	19.68
April	53418	907265	58927	9908	185.48	16.81
May	33553	574522	49301	10973	327.03	22.26
June	5480	41184	1728	453	82.62	26.20
July	2387	7161	126	34	14.10	26.82
Aug	64615	752118	7100	884	13.68	12.45
Total	**384718**	**6661256**	**425536**	**136793**	**355.57**	**32.15**

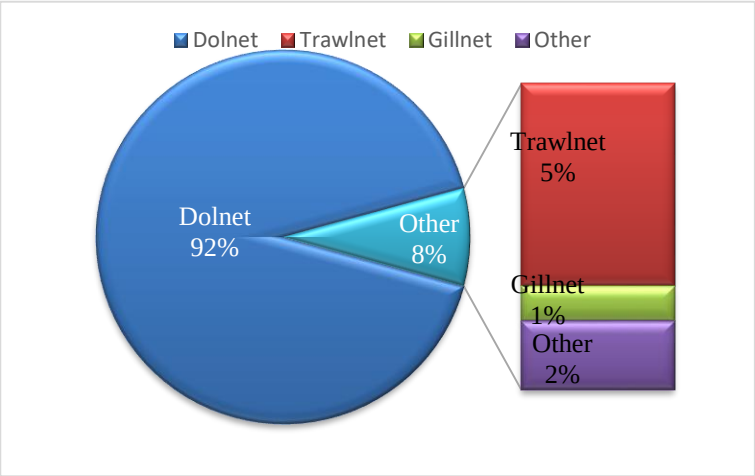

Figure 2.3.1: Fishing gear-wise contributions for a catch of Bombay duck in Gujarat for the pooled season (2014-15 and 2015-16).

The Bombay duck accounted for 29.87% and 34.73% of the total catch respectively during 2014-2015 and 2015-2016 periods. The catch per unit effort for the 1st and 2nd fishing seasons was 274.28 kg and 501.10 kg respectively. Analysis of catch data per month revealed two distinct peak seasons, one extending

from September to January and the other from March to May. Regarding the contribution of fishing gears to the catch, the dolnets dominated with a significant share of 92% of the catch, and the remaining 8% was by trawls, gillnets and several other different types of fishing gear (Figure 2.2).

The seasonal trends observed in catch rates during September-January and March-May periods in the present study are consistent with previous research findings (Ghosh et al., 2009; Khan, 1985, 1989; Khan et al., 1992). Traditionally, the static phase of coastal fishing on the west coast of India begins in September and lasts until January. Subsequently, the fish migrate to deeper waters during the dynamic phase and resurface again in large schools the following September-October (Banerji, 1969; Ghosh, 2014; Ghosh, et al. 2009; Kurian and Kurup, 1992).

The first season (2014–15) recorded an annual catch of 67,703 tons, while the second season (2015–16) recorded a higher catch of 69,089 tons. However, the fishing effort decreased from 247 thousand units in the first season to 138 thousand units in the second season. Catch rates (CPUE) showed significant fluctuations, with a minimum of 274.28 kg in 2014-2015 and a maximum of 501.10 kg in 2015-2016. Interestingly, the catch rates of 77.5 kg and 114.88 kg reported for Nawabandar, Saiyad Rajpara and Jafrabad between 1976 and 1982(Khan 1985, 1989) were lower as compared to the results of the current study. Other studies in the region have also documented fluctuating catch rates, such as 409.64 kg in 2003–2006 (Ghosh et al., 2009) and 378.6 kg in 2006–2009 (Ghosh, 2014).

Chapter 3: Food and Feeding habits

3.1 Introduction

Food is a basic requirement for all life forms and plays a critical role in controlling and influencing the development, fertility, migration and abundance of fish populations. Fish nutrition and growth are influenced by a combination of ecological and innate biological factors. Digestion is closely linked to body size and the type of food consumed (Orians, 2016). Numerous studies have examined the diet and feeding behavior of the Bombay duck in both Indian (Balli, Chakraborty and Jaiswar, 2006; Ghosh, 2014; Kumar et al., 2012) and international waters (Huiqun et al., 2004; Lin, Zhu and Li, 2010; Pan and Cheng 2013; Zhang and Jin, 2014).

3.2 Material and Methods

The food intake and eating habits of 1,298 specimens of the Bombay duck were examined, the size of fish was between 10.5 and 35.1 cm in total length and wet weight between 7 and 270 grams. Assessment of feeding intensity was based on visual inspection of stomach distension and amount of food contents, categorized as full, ¾ full, ½ full, ¼ full, trace or empty stomach (Al-Marzouqi et al., 2009; Muthiah, 1994). Among these, full and ¾ full stomachs were classified as indicating active feeding, while ½ full and ¼ full stomachs were categorized as moderate and weak feeding, respectively.

To assess the importance of different foods in the diet, the occurrence method described by Hyslop (1980) was used. Furthermore, various indices including gastro-somatic indices (GaSI), absolute importance indices (AI) and composite indices were used to analyze the food consumption and feeding behavior of Bombay duck.

3.3 Results and Discussion

Analysis of stomach contents revealed that the Bombay duck primarily consumed finfish and crustaceans. These two categories accounted for 91.19% of the diet in 2014-2015 and 98.10% in 2015-2016. The proportion of crustaceans in its diet decreased from 58.79% in 2014-2015 to 48.11% in 2015-2016, while the proportion of fish decreased from 32.40% in 2014-2015 to 49.99% in Period 2015-2016 increased. Crustaceans had the highest abundance (F) in all years, during study period.

Analyses of the two years pooled diet data revealed that crustaceans made up 52.48% of the diet in Bombay duck, finfish made up 42.79%, and remaining diet (4.73%) consisted of miscellaneous materials such as cephalopods and digested debris. This study confirmed that the

Bombay duck is a carnivorous species whose diet consists predominantly of *Acetes* spp. (34.29%), *Bregmaceros mcclellandi* (24.96%), *Nematopalaemon tenuipes* (12.09%) and *Solenocera crassicornis* (5.39%).

Monthly analysis of the diet of the Bombay duck revealed that the main prey items were *Acetes* spp., *B. mcclellandi*, *N.tenuipes*, *C. dussumieri*, *S. crassicornis*, crabs, *Cynoglossus* spp., *H. nehereus*, *Otolithes* spp., *Johnieops* spp., *Loligo* spp., *Trichiurus* spp., *Sepia* spp., *Apogon* spp. and digested material. The highest percentage of incidents were recorded in November (45.39%), closely followed by May (45.14%) and February (43.06%). In contrast, the lowest percentages were observed in January (18.49%), April (23.10%) and September (28.93%).

Among the prey items *Acetes* spp. consistently formed the dominant part of the diet. *B. mcclellandi* was the second most frequently consumed prey in all months of the study. The highest percentage of occurrences were observed in September (46.15%), followed by January (38.41%) and April (33.40%). However, the lowest percentages were recorded in October (15.85%), December (17.19%) and September (19.63%). Analysis of stomach contents revealed that the diet of Bombay duck consisted mainly of two groups: crustaceans and finfishes, which accounted for 99.72%. The molluscs formed 0.07% and the digested matter 0.21%.

The study showed that the Bombay duck, found on the west coast of India, is a carnivorous species with facultative cannibalistic tendencies. The predominant diet consisted of crustaceans and finfishes, while molluscs and various other groups played a minor role. While crustaceans predominated in the stomach contents in 2014 and 2015, finfish took over the majority in 2016. *Acetes* sp. has consistently been identified as a key prey item in the diet of Bombay duck throughout the study period, aligning with previous findings (Balli et al., 2006; Ghosh, 2014; Ghosh et al., 2012; Jaiswar and Chakraborty, 2005; Kumar et al., 2012).

Acetes spp. were the most frequently consumed food and accounted for the highest dietary volume (%O) with a proportion of 74.59% and 71.87% in males and females, respectively. The two estimated feeding indices showed that both males and females showed a preference for dominant foods groups. This corresponds to 52.03% and 37.79% of the Index of relative importance (IRI) for male and female, respectively. Based on the inter-annual variations in the diet composition of Bombay duck from 2014 to 2016 (pooled data), the estimated values for *Acetes* spp. were 76.73% in 2014, 68.62% in 2015, and 40.94% in 2016.

There was a notable shift in food preferences during the monsoon season, with fish becoming the dominant food source with an estimated IRI of 56.65. In contrast, crustaceans were predominant in the pre and post-monsoon periods, with estimated IRIs of 70.76 and 69.28 respectively. At the same time, the percentage of the index of absolute importance (%AI) for *Acetes* sp. as the primary dietary component was calculated as 45.41% for male and 40.88% for female. *Acetes* spp. remained the dominant food with 50.69% of the diet, followed by *B. mcclellandi* with 30.70% and *N. tenuipes* with 9.25%. Throughout the study period, these three prey items consistently made up more than 90% of the stomach contents. Other prey items found in the diet of the Bombay duck included contributions from *C. dussumieri* (4.93%), *H. nehereus* (1.92%), *S. crassicornis* (1.33%), and *Trichiurus* spp. (0.45%). It is noteworthy that 23.93% of the stomachs were empty during the study period.

Seasonal variations in IRI reflect changes in food availability and selectivity of the Bombay duck in response to prey availability. These variations in diet are primarily associated with changes in the abundance of prey species. *Acetes* spp. is the main prey animal found mainly in the pre- and post-monsoon period, although it is less common during the monsoon season. Due to their short life cycle and high reproductive activity, *Acetes* spp. are available throughout the marine ecosystem, making them an important part of the diet of Bombay duck. The peak of Bombay duck landings typically occurred between September and June, with the highest landings occurring between October and December (Srinath, 2003).

Furthermore, the results suggest that *Acetes* spp. make up a significant portion of the diet, with IRI values as high as 70.15 during the pre-monsoon period (February to May) and 68.45 during the post-monsoon period (October to January). This highlights the important role and preference of *Acetes* spp. in the diet of Bombay duck in the region and its crucial role in sustaining the Bombay duck population. Further, it also highlights the importance of this prey in the management of the Bombay duck fishery on the west coast of India. Among finfish species, *N. tenuipes* plays a role in both pre- and post-monsoon periods, while *B. mcclellandi* is essential during the monsoon season. Additionally, the juveniles of Bombay duck have been observed in the stomach contents of fish throughout the year, with the highest numbers recorded during the monsoon season, suggesting cannibalistic feeding behavior within the species.

The condition of stomachs in males were as follows: empty stomachs (45.12%), ½ full (19.01%), ¾ full (10.83%), ¼ full (9.95%), completely full stomachs (gorged) (9.24%) and traces

of stomach contents (5.86%). In comparison, the proportion in females were: empty stomachs (37.98%), followed by ½ stomachs (19.20%), ¼ stomachs (15.50%), full stomachs (11.38%), ¾ stomachs (11.10%) and traces of stomach contents (4.84%). The presence of empty stomachs indicates the ingestion of tiny organisms that have undergone digestion.

The examination of the feeding intensity over the study period showed that there was a high percentage of empty stomachs across all months. A remarkable prevalence of empty stomachs is a characteristic feature of piscivorous fishes (Arrington et al., 2002; Conover and Juanes, 1994; Qasim, 1973; Tolonen ,1997). The relationship between feeding intensity and fish length in the pooled samples showed clear patterns. Active feeding is most pronounced among fishes with the length ranging between 210-224 mm and accounted for 25.56% of the observed individuals, while poor feeding occurs mainly in the group with a length range of 315-329 mm and accounted for only 1.20%.

For males, the lowest feeding intensity is observed particularly in the length groups 195–209 mm (51.73%) and 180–194 mm (39.61%). In contrast, female in the length range of 210–224 mm recorded the highest proportion of empty stomachs at 23.93%. Monthly variations in feeding intensity in the pooled samples suggest that active feeding peaks in January (22.54%), followed by September (12.39%), December (12.33%) and November (11.05%). Conversely, moderate and poor diet levels are lowest in April (18.62%) and August (7.41%), respectively. Empty stomach symptoms most commonly occur in the months of May (52.43%) and April (50.03%).

In January, both males and females showed the highest active feeding intensity at 19.44% and 24.73%, respectively. Active feeding predominated during January and September, while the prevalence of empty stomach was during April and May. The observed patterns of feeding intensity indicate a significant increase in active feeding during the post-monsoon period, coinciding with the heavy fishing season and mass landing of Bombay duck (Ghosh et al., 2012, 2009; Khan, 1989). This trend is consistent with previous findings by Khan et al. (1992) reported that monthly feeding intensity was highest in the post-monsoon period and lowest during monsoon.

The feeding intensity of Bombay duck was assessed using the Gastro-Somatic Index (GaSI). For males, the GaSI values ranged from 7.26 in November to 3.43 in April, while females had a maximum of 6.47 in August and a minimum of 4.57 in October. When considering size-based estimates, the highest GaSI values were observed in males in the 180–194 mm length group (6.75) and in females in the 150–164 mm length group (6.72). Conversely, the lowest GaSI values in

males were measured in the length range of 300–314 mm (3.55) and in the length range of 220–284 mm (3.86).

Notably, GaSI values of 5.42 (monthly) and 4.10 (size-based) were recorded for males, while females had respective values of 5.31 (monthly) and 5.30 (size-wise). In males, the lower GaSI values were documented in April (3.43) and September (3.92), while for females, these values were observed in October (4.57) and April (4.67). These observations suggest reduced feeding activity due to ovarian maturity, with feeding intensity improving after the completion of the spawning phase (Biswas, 2002).

Dietary analysis of the Bombay duck in this study revealed a predominant consumption of crustaceans and finfish. According to CMFRI, essential prey identified in the gut of *H. nehereus* included *N. tenuipes*, *Acetes* sp., *C. dussumieri*, *H. nehereus* and *B. macclellandi* (CMFRI 2015, 2016) . This feeding behavior is closely related to the anatomical structure of the gastro-digestive system of the Bombay duck, which is characterized by considerable expansion and allows the consumption of much larger food items in relation to its body size (Huiqun et al. 2004).The results of this study are consistent with previous studies by Wei and Jiang (1992), Lin et al. (2010) and Pan and Cheng (2013), which confirms the evolution of the Bombay duck into a fully piscivorous species.

Chapter 4: Reproductive biology

4.1 Introduction

Reproduction plays a key role in fish biology and has a direct impact on recruitment and overall abundance of fish stocks. Factors such as the availability of time, resources and suitable breeding sites have a significant impact on reproductive success (Crossin et al., 2004; Healey, Lake and Hinch, 2003). Understanding reproductive patterns and mechanisms is of paramount importance as it provides us with important tools for assessing the reproductive fitness of fish stocks (Lambert et al., 2003). Various aspects of an organism's reproductive approach and strategy are influenced by factors such as size, age of maturity, fecundity, spawning timing (Stearns, 1992), and population characteristics such as body weight, sex ratio and egg viability, as well as hatching success (Lambert et al., 2003). However, it is important to note that many of these traits exhibit significant spatial and temporal variation due to the different environmental and biological conditions experienced by different populations (Stearns, 1992). Furthermore, environmental variables have a significant impact on a population's ability to attract mature individuals (Fowler, McLeay and Short, 2000). Ideally, any assessment should prioritize these characteristics and incorporate effective fisheries management strategies aimed at achieving sustainable yields from fish species (Yoneda et al., 2002).

Important reproductive information for fish populations, such as spawning time, spawning habitat, size, age of maturity (L_{50}), and sex ratio, forms the backbone of most research related to fisheries stock assessment and management strategies (Morgan, 2008). An important measure in this context is the Gonado-Somatic Index (GSI), which represents the ratio of the gonad weight to the total body weight of the fish (Fagbenro, Olaniran and Esan, 1991). This index serves as a widely accepted indicator of gonadal development, reproductive biology and spawning maturity of fish (Cubillos and Claramunt, 2009). Ideally, a fish's GSI increases with age and decreases sharply after spawning. The GSI primarily helps in determining the spawning time of fish as the gonads of female fish grow in preparation for spawning (Biswas, 1993).

Reproduction is an important physiological process that is essential for fish survival. Fecundity, a term denoting the amount of vitellogenic or mature ova or eggs present in a female before the subsequent spawning phase, shows variation both within and between species (Wootton, 1990). Estimating the amount of eggs a female produces over the course of a season is a major challenge because determining the number of eggs produced depends on the fecundity of the group or spawning frequency (DeVlaming, 1983).

Fish fertility is characterized by the number of developing eggs in the ovary, a parameter that progressively increases during the spawning season (Melville-Smith, 2008). During their reproductive cycle, certain fish species release egg clusters (Bani and Moltschaniwskyj, 2008). The most reliable estimates of annual fecundity are used in population assessment models for various species (Nichol and Acuna, 2001). The quantity, quality and size of eggs released during the spawning season play a critical role in the reproductive success of fish populations (Rickman et al., 2011). Accurate information about the spawning and maturation of commercially caught fish species is of great importance for fisheries management, especially for the protection of spawning stocks (Yoneda et al., 2002).

Several studies have been conducted in India and other countries to investigate various aspects of the reproductive biology of the Bombay duck (Balli et al., 2006; Bapat, 1970; Bapat, Banerji and Bal, 1951; Dash et al., 2018; Deshmukh and Kurian, 1980; Fernandez and Devaraj 1996; Ghosh, 2014). Ghosh (2014) reported that during 2006 to 2009 period, females of Bombay duck dominated in the commercial catches with an overall sex ratio of 1.05. A significantly higher number of females was observed in October and November ($p<0.05$), while males were more abundant in February. *H. nehereus* attained sexual maturity when it reached a total length of 214.5 mm, with gonad development and sexual maturity beginning at 145 mm. Mature females were observed in all months, with the highest frequency during April to June. The average number of eggs per gram of body weight ranged from 94.8 to 1080.6, with an average of 388.3.

Khan et al. (1992) reported the male to female sex ratio as1:0.9 off the coast of Saurashtra. The majority of females were observed in the resting or developing ovarian stage throughout the year, except in May, when mature females were less common. Higher spawning periods were recorded during December-January and June, with egg counts ranging from 17,075 to 79,631 for fish having a length range between 195 to 315 mm. Average fecundity was estimated at 340 eggs per gram of fish body weight. Kurian (2000) estimated the average length at sexual maturity to be 230 mm. The ratio of male-to-female decreased as fish increased in size. Due to the presence of immature, maturing, gravid, and spent individuals throughout the year, the Bombay duck has been categorized as a continuous breeder. Fecundity increased with increasing fish length but showed a relatively linear relationship with weight. Fecundity increased with each spawning event due to a reduction in ova size.

4.2 Material and Methods

To collect data on the reproductive biology of the Bombay duck, fish were dissected to determine their sex and developmental (maturity) stage. The ovaries were weighed and classified according to the International Council for the Exploration of the Sea (ICES) Scale (Lovern and Wood, 1937; Wood, 1930). The Gonadosomatic Index (GSI) was determined using the method described by June (1953), and the sex ratio was calculated using the Chi-square test (Snedecor and Cochran, 1967). For determining length at first maturity, females in stage III and above were considered mature. Fecundity was estimated using a gravimetric technique (MacGregor, 1957), and the data were calculated using the formula proposed by Bagenal (1978). Additionally, logarithmic equations were used to assess the linearity of fecundity with total length and wet weight relationships using the following equations

Log F = a + b * Log BW

Log F = a + b * Log TL

where F represents fecundity, BW is total body weight (g), TL is total length (cm), and 'a' and 'b' are regression constants:

4.3 Results and Discussion

Gonadosomatic index (GSI) values for female showed significant fluctuations throughout the year. The highest GSI for females was observed in August at 24.75, while the peak value for pooled samples was observed in April at 13.04. Conversely, the lowest GSI for females was recorded in December with a value of 2.12, and for pooled samples the lowest value of 0.46 was in February. The highest GSI value of 2.09 was recorded for male in January. The decline in GSI values in February was mainly attributed to spent gonads. A length-based analysis revealed that the highest mean GSI values were observed in the length range of 135–144 mm, reaching 33.32, while the lowest values were observed in the range of 165–174 mm with a GSI of 0.76.

The distribution of the male to female ratios varied from month to month, ranging from a lowest ratio of 1:0.80 in August to a highest ratio of 1:2.09 in April. In commercial fish landings, the males dominated till the fishes attained a length of 194 mm in length, while females with the total length ranging between 195 and 324 mm dominated. Analysis of sex ratios in different length categories revealed significant differences in the ratio of males to females with a significance level of 5%. Overall, this study found a sex ratio for the *H. nehereus* population of 1:1.22, indicating general female dominance. Furthermore, the minimum size at which first maturity was observed

in females was estimated to be 221 mm (Figure4.1). The length at which 50% of the female fish reached maturity was determined to be 295.19 mm.

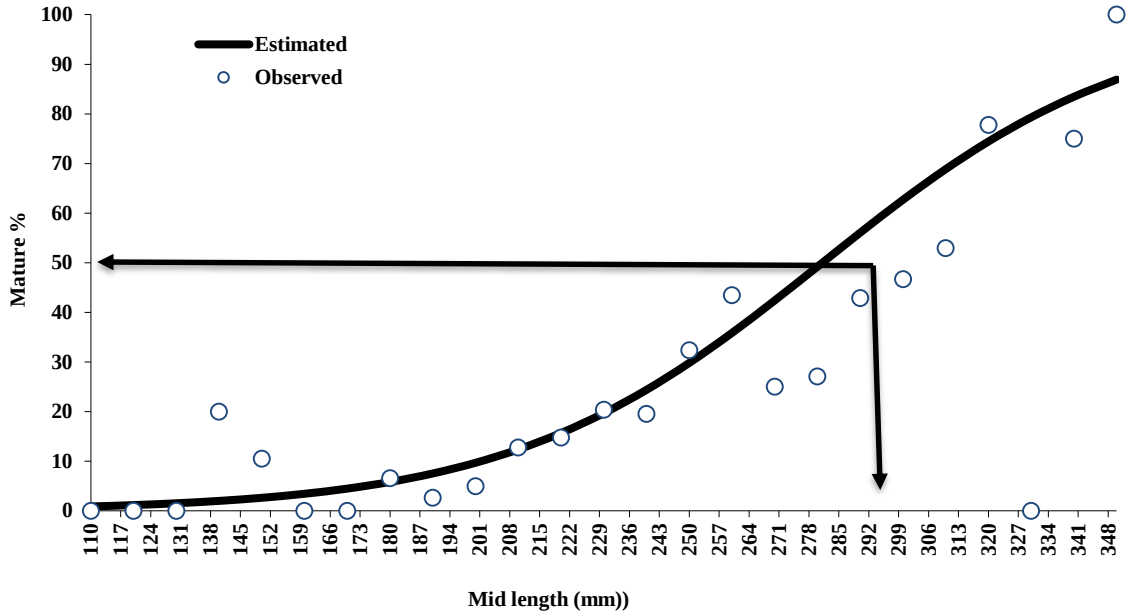

Figure 4.1: Length at first maturity of *H. nehereus* (pooled female)

When examining the reproductive stages of the Bombay duck, it was found that stage VI (mature ovary) was prominent and accounted for 10.31% of observed samples in October. The maturation stage of mature ovaries (stage VI) showed two distinct peaks, one from September (7.41%) to November (2.65%) and another from March (1.75%) to May (2.86%). Stages I to III were observed throughout the year. The presence of stage VII (spent ovaries) was noted in November, April and May. The highest annual spawning rates were documented in October and April at 45.36% and 51.06%, respectively.

The estimate of Bombay duck maturity was based on the analysis of 225 specimens measuring between 142 and 351 mm in total length and weighing between 13 and 270 g. Gonad weight ranged from 1.179 g to 30.587 g and fecundity ranged from 12,063 to 1,14,652 eggs. The highest relative fecundity was observed in August (1213.44) for a fish measuring 248.75 mm and weighing 75 g, followed by April (692.92), January (672.82) and November (650.18) for a fish with a size of 225.44 mm and a weight of 232.32 mm and 256.46 mm, respectively. Analysis of monthly variations in oocyte diameters revealed that the maximum oocyte diameter of 0.592 mm was observed in October, while the minimum oocyte diameter of 0.276 mm was measured in February. During the entire study period, the annual egg diameter of the Bombay duck ranged

from 0.196 to 0.843 mm. Fecundity has been found to increase with both increasing body length and increasing body weight.

The relationship between fecundity (F) and total length (TL) of fish showed a linear trend, expressed by the equation: Log F = -0.95523 + 2.3024 log TL. The correlation coefficient (r) was 0.43373, indicating a significant ($p<0.01$) relationship between these variables. Likewise, fecundity and body weight showed a linear relationship, and the regression equation was presented as log F = 0.68519 + 3.2574 log BW. The correlation coefficient (r) was 0.44021, indicating a significant association ($p<0.01$). In addition, the logarithmic relationship between fertility and ovarian weight (OW) was expressed by the equation: Log F = 1.0444 + 3.598 log OW. The high correlation coefficient (r) value of 0.96292 indicated a highly significant ($p<0.01$) relationship between these two variables.

Reproductive processes in fish exhibit significant variability that depends on species-specific traits and life cycle variables. These include factors such as sexual preferences, parental considerations, spawning patterns and fecundity (Murua and Saborido-Rey, 2003; Teletchea et al., 2009). Parameters such as sex ratio, maturation, gonadosomatic index and size at first sexual maturity are important tools for assessing the reproductive fitness of a population. It is noteworthy that most tropical marine fishes reach maturity and begin spawning within their first or second year of life (Qasim, 1973). Numerous studies have used the Gonadosomatic Index (GSI) as a valuable marker for tracking changes in gonadal development and maturation in fish from early stages to maturity, thereby providing insights into the different phases of the reproductive cycle (Yeldan and Avşar, 2000).

Various environmental factors such as water conditions, photoperiod, precipitation and temperature were found to have a significant impact on the reproduction of *H. nehereus*. However, pH, alkalinity and dissolved oxygen had a negligible influence. Based on the Gonadosomatic Index (GSI) values, it was observed that the onset of maturation in *H. nehereus* occurred in May (11.29) and the gonads matured in August (24.75). The variation in GSI values in this study suggests that elevated temperatures may have triggered the onset of ripening. As suggested by Wooton (1999), temperature is a key factor in the development of the reproductive system. The transition from April to August, coinciding with the rainy season, causes a slight increase in water temperature, as a result of which fish begin to spawn. Conversely, the lower GSI values in December, January and March provide evidence of a more environmentally dependent reproductive system in *H. nehereus*

compared to other teleost fishes (Papoulias, Chapman, and Tillitt 2006; Wootton 1999). Furthermore, long-term exposure to pollutants can reduce GSI values (Louiz, Ben-Attia, and Ben-Hassine, 2009; Pieterse, 2004).

Sex ratio analysis revealed that females were present in all length groups and there was a significant deviation from the expected sex ratio of 1:1 ($p<0.05$). This dominance of female in the fishery is consistent with previous studies conducted in the waters of Mumbai (Bapat, 1970), the Sundarban Estuary (Khan, 2002) and the waters of Saurashtra (Ghosh et al., 2009). Despite an estimated sex ratio of 1:1.22, the proportion of large males in the current study was lower than that of females. The numerical difference between the sexes during fish maturity could be attributed to several factors, including differences in mortality rates between males and females, unique behaviors, or increased vulnerability of fishers to fishing (Lambert et al., 2003; Schaefer, 2003). However, the skewed sex ratio was not statistically significant.

The spawning season and the presence of gravid and mature females were constant throughout the year, with a peak in summer, consistent with previous findings on the west coast of India (Bapat et al., 1951; Ghosh, 2014; Khan et al., 1992; Kurian and Kurup, 1992). The estimated size at maturity (L_{50}) for *H. nehereus* was 295.19 mm. In many species of fish, females tend to take a little longer to reach maturity than males. This difference may be attributed to the fact that females devote more energy from somatic development to gonad development and reproduction, which requires a longer juvenile phase if they wish to attain a larger size before reaching maturity (Miller and Kendall, 2009).

Research in various locations including Saurashtra Coast (Ghosh, 2014; Khan 1989; Khan, et al. 1992), Mumbai coast (Balli et al., 2006; Bapat, 1970; Bapat et al., 1951; Kurian, 2000; Kurian and Kurup, 1992) and the Sundarbans (Khan, 2002) have reported different values of L_{50} ranging from 200 mm to 230 mm for the Saurashtra coast (Ghosh, 2014; Khan, 1986a; Khan et al., 1992) higher values for size at first maturity in females, ranging from 214.5 mm to 266 mm. in present study. These variations can be attributed to the complex interplay of genetic and environmental factors that influence the age and size of fish during sexual development (Stearns, 1992). In addition, environmental factors, particularly precipitation and water temperature, play an important role in influencing a fish's sexual development (Pawson, Pickett and Witthames, 2000).

Fecundity increased with fish size or body weight, with absolute fecundity estimates ranging from 12,063 eggs to 1,14,652 eggs and the mean being 47,085. These estimates are consistent with

previous fecundity studies for *H. nehereus* in the northwest coast estimated at 89,600 by Fernandez and Devaraj (1996), between 14,600 and 1,46,400 in Mumbai waters by Bapat (1970) and between 5,467 and 1,02,079 in the waters of Saurashtra reported by Khan et al. (1992) and Ghosh (2014) in Mumbai waters between 21,182 and 1,16,067 by Balli et al. (2006) and in the Sundarban area between 18,156 and 92,012 by Kumar et al. (2016).

The relative fecundity of *H. nehereus* varied from 117 to 4,771 eggs per gram of fish body weight, with a mean of 628 eggs per gram of fish body weight. The mean estimated relative fecundity in the present study was higher than previous reports of 314 eggs per gram in Mumbai waters (Balli et al., 2006) and 388 in Saurashtra waters (Ghosh, 2014). Several factors influence fecundity, including fish physiological status (Marshall and Frank, 2011), energy consumption (Domínguez-Petit, Saborido-Rey, and Medina, 2010), environmental variables (Korta et al., 2010), population density (Kim et al., 2006), and previous investments in the reproductive cycle (Kjesbu et al., 2011) in female fish during spawning.

The constant presence of mature eggs in mature ovaries throughout the year suggests that individual fish spawn continuously throughout the year. This observation is consistent with previous findings from Mumbai and Saurashtra waters (Deshmukh and Kurian, 1980; Ghosh, 2014). However, earlier studies (Bapat, 1970; Khan et al., 1992) did not produce results consistent with the current findings. This discrepancy may be due to the possibility that previous studies resulted in a lower proportion of adult females in commercial dolnets. As fishing practices have evolved, dolnetters have been operating in deeper waters in recent years, resulting in higher numbers of spawners in the catch.

In the regression equations, the total length (TL) and body weight (BW) of the fish were found to have a highly significant positive influence on their fecundity ($p<0.001$). This relationship indicates that fecundity is linearly related to total body size of fish, suggesting that reproductive performance increases with body size (Musallam et al., 2006). Kordian (1998) found that in fish, fecundity increases faster than weight with increasing length. Fecundity is inversely proportional to weight rather than length (Ali and Kadir, 1996; Wootton, 1973). The low positive correlation coefficients (r^2) obtained in this study are similar to those found in studies by Anetekhai et al. (1990), Oso et al. (2011), and Akponine and Ayoade (2012) were determined. These results show that fecundity not only depends on size but can also be influenced by the availability of food resources.

Chapter 5: Stock assessment and population dynamics

5.1 Introduction

The length-weight relationship(LWR) of the animal provides information about its level of development (Okgerman, 2005). Calculating the weight of live fish in the field is a challenging and time-consuming task (Morato et al., 2001) and the LWR plays an important role in population dynamics and fisheries science (Sivashanthini, Gayathri, and Gajapathy, 2009) . In addition, it is used to estimate biomass based on length perception and condition of fish, and this relationship is useful for correlating the life histories of specific species between sites (De la Cruz Agüero et al., 2011; Moutopoulos and Stergiou, 2002). Overall, estimating LWRs can provide important information for fisheries managers and is helpful in determining improvement in fish population rates and their flow (Anderson and Gutreuter, 1996). Additionally, length-weight relationships can help estimate weight when more important species exceed limits or when standards of use are inadequate.

The significant changes in the biomass of the fish and its general condition were studied by several researchers (Kesteven, 1947; Tester, 1939). Several reports on the length and weight relationship for Bombay duck have been published by researchers from Indian and international marine waters (Bapat, 1970; Bapat et al., 1951; Biradar ,1987; Ghosh et al., 2009; Khan, 1987; Khan et al., 1992; Kurian and Kurup, 1992; Laga et al., 2015; Putri, Samiaji and Nurrachmi, 2013). Age determination and growth parameter estimation play a key role in fisheries management and provide important data for fish stock assessment (Çoban et al., 2013; Lou et al., 2007). These parameters are crucial for evaluating various biological and physiological characteristics, such as age at 50% maturity, stock density, yield-per-recruit, and stock variance in response to habitat (Robinson and Motta, 2010; Sulikowski et al., 2007).

Abiotic factors such as temperature, light and salinity also have a significant influence on fish physiology (Björnsson, Stefansson and McCormick, 2011; Poissant et al., 2007). Furthermore, fishing practices can have a profound impact on fish growth and population dynamics (Alcaraz and García-Berthou, 2007; Halpern and Warner, 2002). In an exploited fish stock, mortality occurs due to fishing (fishing mortality, F) as well as natural causes (natural mortality, M), which include factors such as advanced age, predation, disease, food shortages, and competition (King, 2013; Sparre and Venema, 1998). Typically, juveniles have a higher natural mortality rate, which decreases with increasing length and size (King, 2013; Lorenzen, 2006). Because it is often

difficult to estimate natural mortality in fish directly, indirect methods are used to estimate these rates (Sigler, 1999; Vetter, 1988).

Natural mortality of fish is often estimated using empirical equations. Pauly's equation (2007), for estimating the natural mortality includes the ambient water temperature. The von Bertalanffy equation takes into account the growth coefficient (K), and the asymptotic length ($L\infty$) for estimating the growth of the fish. Rikhter and Efanov (1976) also estimated natural mortality based on age at 50% of maturity, and Alagaraja (1984) developed a method based primarily on fish lifespan (Sparre and Venema, 1998). However, it is important to note that empirically estimated values of natural mortality can vary significantly (Burton, 2001). Therefore, caution should be exercised when these estimates are used in population dynamics models (Vetter ,1988).

Fishing activities also reduce the population size and fishing-related mortality rates are directly related to the level of fishing effort (Lorenzen, 2005). Excessive fishing can affect recruitment by depriving fish of their reproductive opportunities. Annual instantaneous all-cause mortality (Z) can be determined by either length-based methods (Gayanilo Jr. and Pauly ,1997) or age-based methods (Ricker. 1975). Several studies have reported the age and growth of Bombay duck from Indian and international waters (Balli et al., 2011; Fernandez and Devaraj, 1996; Ghosh et al., 2009; He et al., 2018; Kurian and Kurup, 1992; Pan and Cheng, 2013; Pitcher et al., 1998; Sarker et al., 2018).

5.2 Material and Methods

The present study analyzed 1,523samples of Bombay duck, including 646 males and 789 females, as well as 88 indeterminate specimens. The length-weight relationship was calculated as $W = aL^b$ and the function was linearized after a logarithmic transformation (Cren, 1951). The parameters were estimated using the least squares method using log (TL) = X and log (TW) = Y. The regression coefficient or regression line (b) was calculated using the following equation:

$$b = [\sum XY - (\sum X) * (\sum Y) / N] / [\sum X^2 - (\sum X)^2 / N]$$

The formula $a = \bar{Y} - b\,\bar{X}$ is used to obtain the intercept '*a'*. The $\bar{X}$ and $\bar{Y}$ represent mean values of X and Y, respectively, and 'N' represents the total number of samples. In order to determine whether the values of '*b*' for males and females are significantly different from '3' the student's *t-test* was performed utilizing equation $t = (b - B) / S_b$; Where; B = 3 and S_b = standard error of '*b*'.

The length-based approach described in the FAO-ICLARM stock assessment tool (FiSAT-II) package was used to assess the Bombay duck population (Gayanilo, Sparre, and Pauly, 2005). This method pooled the data and analyzed the length measurements, which were grouped into 15 mm interval classes. The method of Bailey's (2003) was used to estimate the maximum lifespan (t_{max}). Both the Jones and van Zalinge method (Jones and Zalinge, 1981) and the length-converted catch curve (Pauly, 1983) were used to estimate the total mortality parameters. Pauly's method was used to calculate natural mortality. When calculating fishing mortality, natural mortality was deducted from total mortality. Froese and Binohlan (2000) method was used to calculate the exploitation rate (U). Beverton and Holt's relative yield-per-recruitment (Y/R) used length probability and capture at the first capture values as inputs (Beverton and Holt, 1966).

5.3 Results and Discussion

5.3.1 Length-weight relationship

The study analyzed 1,523 samples of Bombay duck, including 646 males and 789 females and 88 indeterminates. The LWR of 646 males (10.5 cm to 32.0 cm and 07 g to 192 g), 789 females (11.9 cm - 35.1 cm and 10 g - 270 g) of 1583 (pooled males and females) of Bombay duck samples were estimated as

Male: $W = 0.094115\ L^{3.03082}$

Female: $W = 0.086950\ L^{3.10494}$

Pooled: $W = 0.077488\ L^{3.18034}$

The corresponding logarithmic equation may be written as

Male: Log W = -2.363234 + 3.0308194*Log L (r = 0.928848)

Female: Log W = -2.442427 + 3.1049447*Log L (r = 0.935918)

Pooled: Log W = -2.55763 + 3.1803379*Log L (r = 0.927971)

The significance of variation of '*b*' for this species relative to the standard value for ideal fish (3.0) was determined using the *t-test* according to the formula equation condition $t = (b\text{-B})/Sb$, with the following results.

Male: t = 3.030819 – 3 / 0.0476339 = 0.6469 (N.S. at 5% and 1%)

Female: t = 3.104945 – 3 / 0.0416523 = 2.5195 (S. at 5% and 1%)

Pooled: t = 3.180338 – 3 / 0.0327476 = 5.5069 (S. at 5 % and 1%)

A total of 1,523 numbers of *H. nehereus* with a M:F ratio of 0.81:1 was collected from the west coast of India. The mean total length and weight of the males were 20.88 ± 3.38 cm and 40.06 ± 28.57 g respectively, while the female figures were 22.24 ± 3.75 cm and 61.62 ± 38.03 g respectively. The data showed that females achieved greater length and weight than males. Previous studies have also shown that the proportion of male and female is different (Firdaus et al., 2013; Putri et al., 2013). The exponent "b" values showed isometric growth for males (3.03) and positive allometric growth (b>3) for females (3.10). Student t-test results suggested that the "b" values for females and the pooled data were significantly different ($p<0.05$).

Females had a higher value of '*b*,' indicating that the cubic weight gain was 3.10 for per unit length, but males had a value of 3.03. The Cube Law explains the length-weight relationship of fish in which the fish maintain a constant shape as '3'. Changes in biomass lead to fish growth, and there are significant differences in isometric growth (Allen 2006). Such significant differences between the sexes of the Bombay duck has been reported previously (Bapat, 1970; Bapat et al., 1951; Ghosh, 2014; Ghosh et al., 2009; Krishnayya, 1968; Kurian and Kurup, 1992; Martin, 1949; Mitra, 2001; Nurul, 2001).

5.3.2 Growth Parameters and Life History

The study conducted on Bombay duck (*H. nehereus*) sampled from the northwest coast of India (Gujarat) between September 2014 and November 2016 provided important insights into growth, mortality rates, exploitation status, and population dynamics. The size of Bombay duck in the study ranged from 105 mm to 351 mm, with notable length classes observed between 345-359 mm and 105-119 mm. The parameters of the von Bertalanffy growth equation were estimated as follows: asymptotic length ($L\infty$) = 366 mm, growth coefficient (K) = 0.98 $year^{-1}$, time at zero length (t_0) = -0.0145 and maximum lifespan (t_{max}) = 3.06 years. The growth performance index (Phi, Ø) was calculated as 3.12, indicating a moderately high growth rate compared to other studies (Ghosh et al., 2009; Liang and Pauly, 2017; Mustafa et al., 1998).

Using the inverse von Bertalanffy equation, the lengths achieved at the end of 1, 2, and 3 years were 230.51 mm, 315.15 mm, and 346.91 mm, respectively. These results are consistent with previous studies but highlight regional differences that are likely influenced by environmental factors such as water temperature and food availability (Ahamed et al., 2012; Froese, 2006).

5.3.3 Mortality and Exploitation

The total mortality coefficient (Z) for Bombay duck estimated in the study was estimated using two methods: the length-converted catch curve method ($Z = 3.32$ year^{-1}) and the Jones and van Zalinge estimate ($Z = 3.929$ year^{-1}). Natural mortality (M) was calculated at 1.6375 year^{-1}, while fishing mortality (F) was slightly higher at 1.6825 year^{-1}, indicating significant fishing pressure on this species. The exploitation ratio ($E = F/Z$) was 0.51, indicating that current fishing efforts are exerting significant pressure on the Bombay duck population. The exploitation rate (U) was estimated to be 0.49, with the lengths at 25%, 50%, and 75% exploitation (L_{25}, L_{50}, and L_{75}) being 156.11 mm, 163.41 mm, and 170.71 mm, respectively.

The results showed that fishing mortality (F) for Bombay duck in the 210-224 mm range peaked at 1.755 year^{-1}, with notable catches observed in the 105 - 119 mm and 195 - 209 mm size groups. Recruitment in the fishery occurred throughout the year, with peaks in May (15.67%) and September (10.56%), indicating sustained fishing pressure throughout the year.

5.3.4 Comparative Growth and Population Dynamics

Comparisons with previous studies highlighted the variability of growth parameters in different regions. Studies by Ghosh *et al*. (2009) reported different growth parameter for Bombay duck off the coast of Saurashtra, reflecting regional ecological differences (Balli et al., 2011; Fernandez and Devaraj, 1996; Mustafa et al., 1998; Sarker et al., 2018). Maximum lengths recorded during this study reached 351 mm, exceeding previous records at various locations, but suggesting stock-specific populations on the west coast of India.

5.3.5 Implications for Management

The results of the study suggest that current fishing pressure on Bombay duck exceeds sustainable levels, as evidenced by an exploitation rate ($E = 0.51$). The analysis of the yield per recruit (Y/R) showed that the maximum relative yield is achieved at an exploitation rate (E_{max}) of 0.661. Beyond this point, the Y/R ratio declines, indicating that current exploitation levels are approaching, but have not yet exceeded, the optimal point for maximum sustainable yield. The observed pattern of exploitation highlights the need for adaptive management strategies to maintain fisheries sustainability (Balli et al., 2011; Mustafa et al., 1998; Sarker et al., 2018).

5.3.6 Regional Variations and Conservation Implications

The study also found significant differences in growth parameters and mortality rates compared to other regions, highlighting the need for region-specific management approaches

(Balli et al., 2011; Kurian, 1989; Mustafa et al., 1998). Conservation efforts should take into account these regional differences in biology and exploitation pressures to ensure the long-term viability of Bombay duck populations (Fernandez and Devaraj, 1996; He et al., 2018; Liang and Pauly, 2017).

Chapter 6: Executive Summary

The thesis provides a comprehensive analysis of the Bombay duck fishery, focusing on its distribution, biology, and fisheries trends along the west coast of India. It highlights the ecological and economic significance of the species, which is predominantly found in the coastal waters of South Asia, the Middle East, and parts of Southeast Asia. In India, the fishery is primarily concentrated in Gujarat and Maharashtra, accounting for approximately 90% of total landings. The main fishing method involves the use of stationary dolnets. Seasonal variations in abundance are influenced by factors such as food availability and water temperature.

The study emphasizes the species' critical role in pelagic fish landings along the west coast of India. Its discontinuous distribution, mainly between 18°N and 22°N latitude, is attributed to regional tidal amplitudes. The availability of shrimp and anchovies, which form the primary diet of Bombay duck, supports its population. The research addresses key knowledge gaps related to species biology and population dynamics, which are essential for effective fisheries management.

An analysis of seasonal variations in fishery trends reveals significant fluctuations in landings between 2001 and 2023. The highest recorded landing was 0.1 million tons in 2013, while the lowest was 0.055 million tons in 2022, indicating a possible decline in species abundance or catch rates. The fishery exhibits strong seasonality, with peak catches occurring from September to January and again from March to May. Most fishing operations take place at depths of 20–70 meters, with the highest catch per unit effort (CPUE) recorded in September.

Geographically, the fishery in Gujarat is concentrated in major fishing centers such as Jafrabad, Nawabunder, and Saiyad Rajpara, where dolnets are predominantly used to target the species. The CPUE reaches its highest level in September, accounting for 55.26% of the total catch, while the lowest CPUE of 12.45% is recorded in August.

A dietary analysis of 1,298 specimens revealed that Bombay duck primarily feeds on finfish and crustaceans, which made up 91.19% of its diet in 2014–2015 and 98.10% in 2015–2016. Various indices were used to assess feeding intensity and dietary preferences, highlighting the species' strong reliance on these food sources, which significantly influence its growth and reproductive success.

The study provides crucial insights into the species' reproductive biology, life cycle, and growth rates, emphasizing the need for continuous monitoring to ensure sustainable fishing practices. An analysis of the length-weight relationship (LWR) and growth patterns, based on 1,523 specimens, showed that males exhibit isometric growth, while females display positive allometric growth. Females were found to be generally larger and heavier than males, highlighting significant sexual dimorphism.

The research underscores the importance of age determination and growth parameter estimation in fisheries management. These factors are essential for assessing maturity age, stock density, yield per recruit, and stock variation. Seasonal abiotic factors such as temperature, light, and salinity significantly affect fish physiology. The study also examines the impact of fishing practices on population dynamics, noting higher mortality rates among juvenile fish, which pose challenges in accurately estimating natural mortality.

Between September 2014 and November 2016, Bombay duck samples ranged in size from 105 to 351 mm. Growth parameter evaluations determined an asymptotic length ($L\infty$) of 366 mm, a growth coefficient (K) of 0.98 $year^{-1}$, and a maximum lifespan (t_{max}) of 3.06 years. Mortality assessments indicated an overall mortality coefficient (Z), with natural mortality (M) at 1.6375 $year^{-1}$ and fishing mortality (F) at 1.6825 $year^{-1}$. The exploitation ratio of 0.51 suggests a balance between fishing pressure and population sustainability.

The study concludes that while the Bombay duck fishery remains economically important, the declining trend in landings indicates potential overfishing or environmental changes affecting the population. It recommends implementing sustainable fishing practices, enhancing monitoring and data collection, and adopting adaptive management strategies to ensure long-term viability. These findings provide valuable insights for policymakers and fisheries managers in developing effective conservation and management plans.

Chapter 7: References

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Research Guide